CYCLIC FRACTURE BEHAVIOUR OF PHT PIPING MATERIAL

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ABSTRACT

Primary heat transport (PHT) piping of nuclear reactors has to ensure that sudden catastrophic failure such as during a seismic event does not occur. The leak-before-break (LBB) design concepts of PHT piping therefore requires a thorough understanding of the ductile fracture characteristics of PHT piping material due to the load fluctuation during seismic activity. In this paper, the fracture resistance of SA333 Gr.6 steel used in the pressurised heavy water reactors (PHWR) under monotonic and simulated seismic loading has been investigated. To simulate the deleterious effects of seismic loading, ductile fracture resistance was studied under cyclic tearing loading of various magnitudes of incremental displacements and load ratios. It is noted that the imposition of cyclic unloading during ductile fracture tests results in a dramatic decrease of fracture resistance. The rationale for such drastic reduction in ductile fracture resistance has been discussed.

1 INTRODUCTION

Cyclic fracture resistance is an important requirement in components that are liable to be subjected to seismic loading, and which must retain their integrity nevertheless. Primary heat transport (PHT) piping of nuclear power plants fall into this category, where it must be demonstrated that sudden catastrophic rupture is highly unlikely without prior indication of detectable leakage as part of the leak-before-break (LBB) strategy.

The primary damaging action during seismic events can be approximated to an application of monotonic tearing loading interspersed with periodic load reversals leading to unloading or compression at the crack tip. This leads to fracture in a progressive cyclic manner. For effective LBB analyses of PHT piping components, it is imperative that the resistance of the piping material to cyclic fracture under simulated seismic loading is employed. This is particularly thought to be important since investigations[1-6] have shown that fracture toughness is degraded under seismic loading.

In this paper, cyclic fracture resistance of SA 333 steel, which is a typical PHT piping material, is presented. Cyclic fracture resistance has been quantified through "cyclic" *J-R* curves. The effects of variation in the extent of periodic load reversals and the frequency of such load reversals have been studied. Emphasis has been laid on understanding the response of the material vis-à-vis that displayed during monotonic application of load.

2 EXPERIMENTAL DETAILS

2.1 Material

The SA 333 steel was available in the form of seamless pipes of 406 mm diameter and 31 mm wall thickness. The steel was of C-Mn variety, with 0.18% C, 0.9% Mn, 0.25% Si and low contents of S and P. The ferrite-pearlite microstructure was banded, with a relatively low inclusion content of 0.94%, and a grain size of ASTM 09. The mechanical properties of the steel were: YS=307 MPa, UTS=463 MPa, %El=39.1%.

2.2 Cyclic *J-R* testing

The single specimen technique, popularly used for conventional quasi-static monotonic *J-R* testing, was adapted for cyclic *J-R* tests. Compact Tension (CT) specimens of 50mm x 25mm dimension in LC orientation were used. The loading scheme employed for cyclic *J-R* tests is shown in Fig.1. Throughout a test, loading is implemented at a constant displacement rate. With reference to Fig.1, a pre-defined tearing (or opening) displacement ΔV is imposed prior to reversal of displacement (i.e. leading to closing of the crack) and consequent unloading. Unloading is continued until a load level defined by a (positive or negative) load-ratio (R) is achieved. Depending on the R, this unloading may surpass the elastic range and result in considerable local compressive plasticity in the neighbourhood of the crack tip. On reaching the desired unload level, opening displacement is again resumed up to the point at which displacement had been reversed. The process is then repeated a number of times so that a substantial amount of crack extension is observed to have taken place.

The envelopes of the maximum and minimum peak loads, shown in Fig.1, are a function of ΔV and R, and also of the response of the material to local cyclic plastic deformation and change in the specimen compliance due to extension of the crack. For a typical instance of ΔV and R, the resultant *P*-LLD plot obtained from a cyclic *J-R* test is shown in Fig.2. The test variables are defined in the figure. Tests were conducted with ΔV of 0.15, 0.3 and 0.5 mm, at the following *R*-ratios: 0.9, 0, -0.5, -0.8, -1.0 and -1.2. It may be noted that tests with R=0.9 are essentially conventional single specimen *J-R* test, and serve as an upper limit to cyclic *J-R* behaviour.

A smaller ΔV signifies more frequent periodic unloading superimposed on opening displacements. Variation in ΔV thus can be thought to model the effect of frequency in periodic cyclic loading during seismic activity. The *R*-ratio represents the extent of unloading during seismic activity. The test matrix employed thus encompasses a large range of loading conditions simulating seismic events.

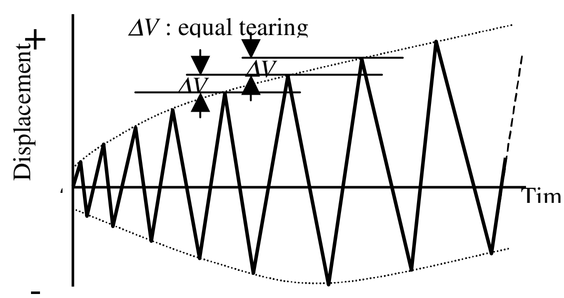

Fig.1: The loading scheme employed for cyclic *J-R* tests. See text for details.

2.3 *J-R* data analysis

Digital data recorded during cyclic *J-R* testing were processed off-line to obtain *J-R* curves. The instantaneous crack length at each instance of load reversal during a test was computed from the compliance calculated from the initial linear elastic part (above 70% of the load at reversal) of the unloading line. It was necessary to correct the compliance for large rotations using formulations available in standards[7]. The validity of application of *J*-integral even when unloading occurs at the crack tip, as has been accepted for periodic unloading during single specimen *J-R* tests by consensus[8], has been assumed. *J* was calculated from the incremental area under the *P*-LLD envelope curve above the baseline $P = 0$. The correction proposed by Joyce and Link[9] to account for crack extension in the loading step has been incorporated in the calculation of J. The η and γ factors in the equation used for computation of J were obtained from relations given by Sumpter[10].

Most investigations[3-6] on cyclic *J-R* behaviour of materials have upheld schemes similar to that outlined above, i.e. employing the tensile area under *P*-LLD envelope, for computation of *J*. Dowling and Begley[11] and Mogami et al.[12] have proposed alternate methods wherein the area is calculated above a baseline determined by the crack closure load and/or the hysteretic area during load reversals has been considered. Such methods are difficult to interpret from the physics of the process involved, and have not been attempted in this investigation.

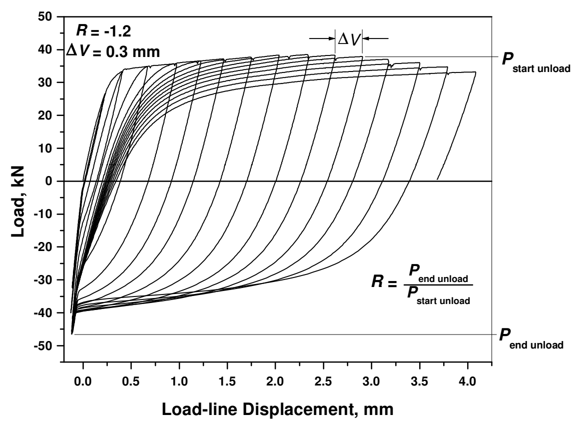

Fig.2: Test data plot for a cyclic *J-R* test on PHT piping material.

3 RESULTS AND DISCUSSIONS

Fracture resistance can be quantified by *J-R* curves, the critical fracture toughness and the tearing modulus. The effects of test parameters on these entities are presented and discussed below.

3.1 Effect of *R* on cyclic *J-R* curves

Fig.3 presents the cyclic *J-R* curves obtained for the various values of *R*. From Fig.3 it is clear that at all values of ΔV, the *J-R* curves for $R = 0.9$ and 0 are not significantly affected by load reversals. Similar observations were made by Rudland et al.[4] for SS 304 and A 106 Gr. B steel. On the other hand, it has been shown by Seok et al.[5] for SA 516 Gr.70 steel and Joyce[13] for 3% Ni steel that *J-R* curves were depressed significantly by reduction of *R* up to $R = 0$. It is thought that the sensitivity of *J-R* curves to variation of *R* above $R \geq 0$ is dependent upon the stress triaxiality at the crack tip. In SA 333 PHT piping material, it has been shown[14] that there is almost a total loss of crack tip constraint prior to the initiation of fracture. A similar case is probably applicable in highly ductile materials like SS 304 and A 106 steel. For higher strength materials like SA 516 and 3% Ni steels, it may be assumed that the crack is subjected to a higher level of constraint, making them sensitive to cyclic unloading effects once the unload is more than a minimal extent (say $R < 0.8$).

Referring to Fig.3 it can be seen that below $R = 0$ leads to progressive lowering of the *J-R* curve quite dramatically. The adverse effect of periodic compressive unloading on the fracture resistance of materials has been reported by various investigators[1-6]. It may also be observed that the lowering of cyclic *J-R* curves with *R* seems to saturate at $R = -1$ for all values of ΔV. Saturation have been reported for SA 516 Gr. 70 steel[3, 5] at $R = -1$, for A 106 Gr. B steel[4] at $R = -0.8$ and for SS 304[4] at $R = -1$. It may be postulated that in the present material this is due to crack face contact at $R < -1$, so that an enhanced level of damage is not able to be accumulated in the crack tip area in spite of the greater extent of unloading. This proposition is borne out by the appearance of cusps in the unloading extremities of cyclic loading loops for R=-1.2. It may be said that cyclic plastic characteristics of the material controls the accumulation of strain in the vicinity of the crack tip, which governs the opening of the crack faces and the manner in which they may collapse against each other during cyclic *J*-*R* testing. A limit to the maximum degradation in fracture resistance observed during cyclic *J*-*R* tests is reached when total crack face contact is established during periodic unloading.

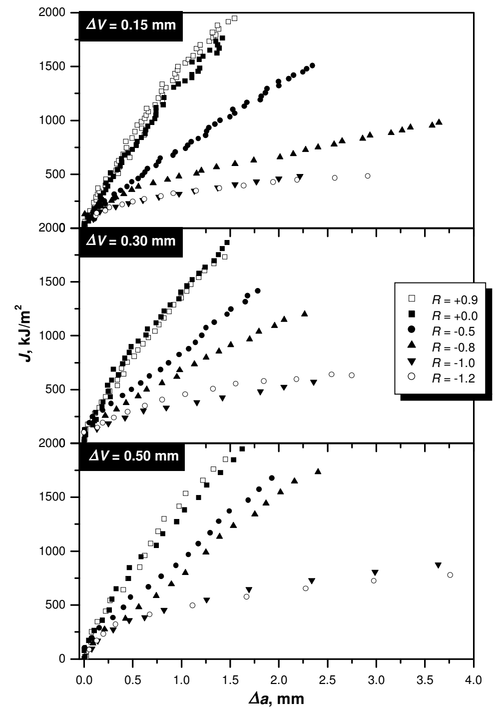

Fig.3: Cyclic *J*-*R* curves obtained for various extents of unloading *R*, grouped together by the tearing displacements ΔV imposed in the tests.

3.2 Effect of ΔV on cyclic *J*-*R* behaviour

Examination of Fig.3 reveals that in the range $0 < R \leq -1$, the nature of the *J*-*R* curves is quite sensitive to the tearing displacement ΔV imposed. In Fig.4, the effect of variation of ΔV is further clarified for three selected values of *R*, representing the three regimes of *J*-*R* behaviour exhibited by the SA 333 PHT piping material.

From Fig.4, for the case of $R = 0$, it is clear that variation of ΔV has no effect on fracture resistance. It is logical to expect an alteration of *J*-*R* curves with frequent load reversals due to superimposition of fatigue effects leading to enhanced crack extension. Kaiser[15] has reported enhancement of crack growth through fatigue contributions resulting in the lowering of *J*-*R* curves for $\Delta V < 62$ μm at positive values of *R* in OX 813 steel. It has also been shown[13, 15] that the crack extension in a cyclic *J*-*R* test can be modelled by a linear summation of crack growth through fatigue contributions and that obtained due to monotonic tearing. In the present investigation, even for the smallest ΔV of 150 µm (0.15 mm), the PHT piping material is observed not to respond to superimposed fatigue processes at $R \geq 0$. This is no doubt due to a relatively insignificant amount of fatigue damage being produced in the SA 333 material.

For intermediate levels of *R*, representatively shown for $R = -0.8$ but equally applicable for $R = -0.5$ and –1.0 as well, there appears to be a significant effect of variation of ΔV. The *J-R* curve is lowered, indicating a deterioration of fracture resistance, with decreasing ΔV. Since a smaller ΔV is synonymous with more frequent load reversal during seismic activity, the behaviour observed is indicative of a synergistic contribution of cyclic plasticity to damage evolution at the crack tip resulting in increased propensity to crack extension. Similar effect of decreasing tearing displacements leading to inferior fracture resistance has been reported by Landes and McCabe[1] for A 508 steel and Seok et al.[3, 5] for SA 516 Gr.70 steel. Using a stress analysis approach Seok and Murthy[3] conclude that tensile residual stresses are induced at the tip of a crack on unloading through zero, and this residual stress aids in crack extension during the imposition of the subsequent tearing displacements in cyclic *J-R* testing. By this logic, a smaller ΔV, due to more frequent through-zero traverse, accumulates higher residual stresses at the rack tip, and causes an enhanced rate of crack extension to be manifested, thereby lowering the *J-R* curve. It may be noted that residual stresses are induced due to the hysteretic nature of cyclic plasticity.

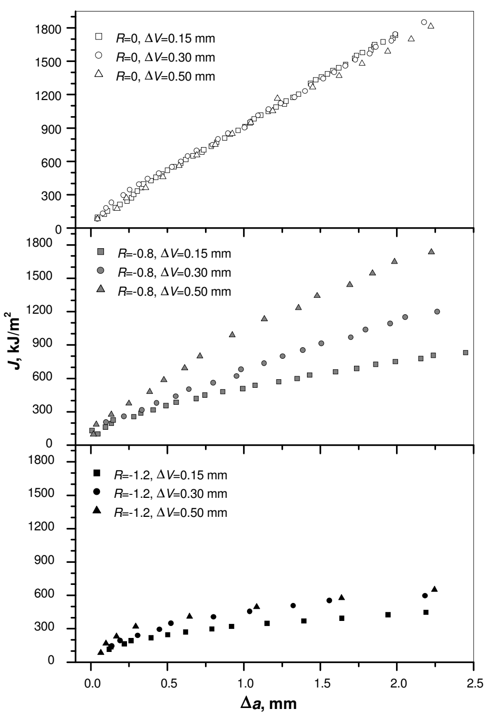

Fig.4: Cyclic *J-R* curves obtained for various tearing displacements ΔV imposed in the tests, grouped together by selected extents of unloading *R*.

It had been shown earlier that the lowering of the *J-R* curve appears to saturate beyond an *R* of –1.0. From Fig.4, for $R = -1.2$, at which damage due to unloading is expected to saturate, it can be seen that decreasing the tearing displacement ΔV results in continuing suppression of the *J-R* curve. The effect of ΔV is however small in relation to that observed at intermediate levels of *R*, indicating that more frequent unloading is not able to appreciably enhance the state of damage at the crack tip beyond saturation levels of *R*.

4 CONCLUDING REMARKS

Considering the total gamut of observations presented in Figs. 3 and 4, the effect of periodic load reversals during cyclic *J-R* testing can be generalised as follows. Each unloading excursion during any test is liable to incorporate damage in the crack tip area. The extent of damage is governed by the nature of cyclic plasticity at the crack tip, which is controlled by the level of unloading, and which is responsible for the manifestation of tensile residual stresses at the crack tip that aid crack extension. The quantum of damage is influenced by the frequency at which unloading excursions take place. Unloading excursions that do not lead to compressive stresses in the specimen are not able to generate appreciable cyclic plasticity at the crack tip, and therefore unable to influence the crack extension behaviour that mainly now takes place through ductile tearing. Since cyclic plasticity is not a critical issue for this type of loading situation, the frequency of unloading will not matter unless it is high enough to bring about a purely fatigue contribution. When unloading leads to compressive stresses, the state of damage at the crack tip is influenced both by the extent of unloading and the frequency at which it occurs. For highly compressive unloading excursions, the fractional damage incorporated in each cycle of unloading is almost unity, resulting in easy propagation of fracture. The effect of frequency of unloading in this case is liable to be minimal, as the damage is so extensive in the fracture process zone at the crack tip that it cannot be enhanced appreciably. The account presented above is developed from observations on the SA 333 PHT piping material being studied, and is applicable for the conditions of cyclic plasticity and crack tip constraints displayed in it.

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